PROCEEDINGS, 47th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 7-9, 2022
SGP-TR-223

Fault and Structure Study for Field Development Strategy in Patuha Geothermal Project

Vicky R. Chandra, Yuris Ramadhan, Ihsan Akmala, Randy W. Atmaja, Rhino S. Sesesega, Chevy Iskandar

PT. Geo Dipa Energi (Persero), Wisma Aldevco Octagon, Jl. Warung Buncit No. 75 Jakarta

vicky@geodipa.co.id

vickyraychandra@gmail.com

Keywords: fault, structure, feedzone, well targeting, lidar, permeability, sweet spot, pts, tracer test, meq, thermal feature, focal mechanism, geophysics, kawah putih, Patuha, geothermal

ABSTRACT

Faults and other local structures are often considered as well targets due to its contribution to the geothermal fluid permeability in the reservoir. There are some conjunction among evidence of surficial faults, fractures, and volcanic features pattern with the occurrence of drilling sweet spots from benchmarking experiences in the world. Based on this assumption, an analysis of surface mapping to indicate the coexisting of faults, fractures, and volcanic features are highly required. Later, these surface structure will be combined by subsurface evidence such as well data and geophysical interpretation. This comprehensive approach will be applied as part of well targeting assessment prior to Unit-2 Patuha Geothermal Drilling Campaign Project in 2021.

The objective of the study is to get a better understanding of the fault and structure pattern of Patuha field and as main component of the well targeting assessment. This study covers the observation from geology regional framework, remote sensing interpretation using LiDAR data, and ground truth mapping for thermal features and geological structure evidence. Whilst the subsurface data derived from PTS, tracer test, and MeQ interpretation will be used to support the interpretation. Finally, the surface and subsurface interpretation will be integrated to see the possible fractures/faults trend continuity within reservoir zone with some of confidence level classification. These faults or fracture will provide a significant input for well targeting and its affected area or known as damage zone.

Generally, the fault and fractures in Patuha are interpreted to have trend of NW-SE coupling with trend NE-SW and some minor N-S direction. These faults are ranked to indicate the possibility of success. The higher rank of faults with common trend of NW-SE and WNW-ESE (Ciwidey-1, Patuha-2, and Patuha-3 faults) and NE-SW trend (Rancabolang Faults) that have been penetrated from several wells before are favorable to be targeted, while the other faults have the lower rank but it may still promising if the new data available. The vertical feed zones are distributed approximately at elevation of 800-1250 masl, 500-700 masl, and 0-150 masl that also being part of well target element.

1. INTRODUCTION

The Patuha Geothermal Field located in West Java province of Indonesia and about 50 kilometers from Bandung city towards Southwest. The Patuha field is situated within a northwest-trending volcanic mountain range, such as Mt. North Patuha, Mt. South Patuha, Mt. Urug, Mt. Puncaklawang, Mt. Pungkur, and other surrounding peaks. The surface thermal manifestation distributed in Patuha field are fumarole area at K.Putih, K.Cibuni and K.Ciwidey, thermal springs are located on south, west and northwest flank of the volcanic highland.

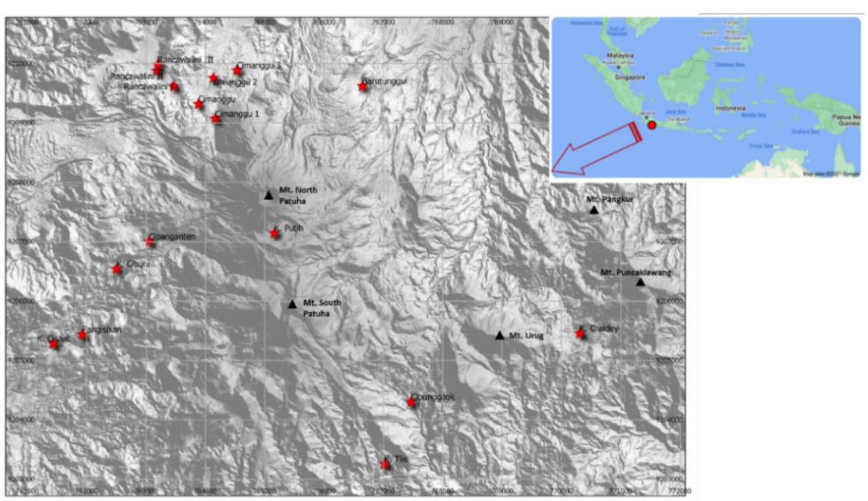


Figure 1: The Patuha Field location with Background Digital Elevation Model from LiDAR.

The exploration survey in Patuha geothermal field started in the late 80's and continued with exploration drilling of 17 TCH (Temperature Core Hole) and of 14 big holes wells in the 90's. These wells are utilized for generating unit I of 55 Mwe and act as production and injection wells. The first drilling campaign was successfully confirming the existence of geothermal resources underneath Patuha field, it is suspected the reservoir fluid is vapor dominated with reservoir extension is elongated, structurally controlled with an area is about 20 square kilometer (Layman, 2003).

Recently, The Patuha Geothermal Project is facing the new development stage to expand the power generating for unit II generation. 12 production wells are planned to drill for producing the additional 55 Mwe of steam with the buffer and to validate the resource and operational uncertainty. The current reservoir study and has dictated to minimize the steam extraction at the same area of unit I and stepping out to explore the reservoir extension laterally and vertically that being planned for the development strategy.

The success ratio of Unit-1 drilling campaign is around 75%. Therefore, the next development campaign should be better due to more survey and well data available. To increase the success ratio and minimize the risk of uncertainty, a proper concept of targeting structure permeability is highly required. The other components of well targeting in Patuha are finding a high temperature area and minimize the reservoir fluid risk also contribute in the well targeting methodology, but will not be discussed in here. Thus, understanding of faults and fractures occurrence and the fluid connectivity path may play the main role as fluid flow driver in the reservoir then being treated as main target in the drilling campaign.

2. METHODOLOGY AND DATA AVAILABILITY

The main challenge in Patuha subsurface permeability is no available borehole image logs to see it's connection with surface fault and structure. To encounter the problem, The flowchart below (figure 2) is developed as best practice in doing assessment of fault and structure of Patuha field that might contribute to the well permeability.

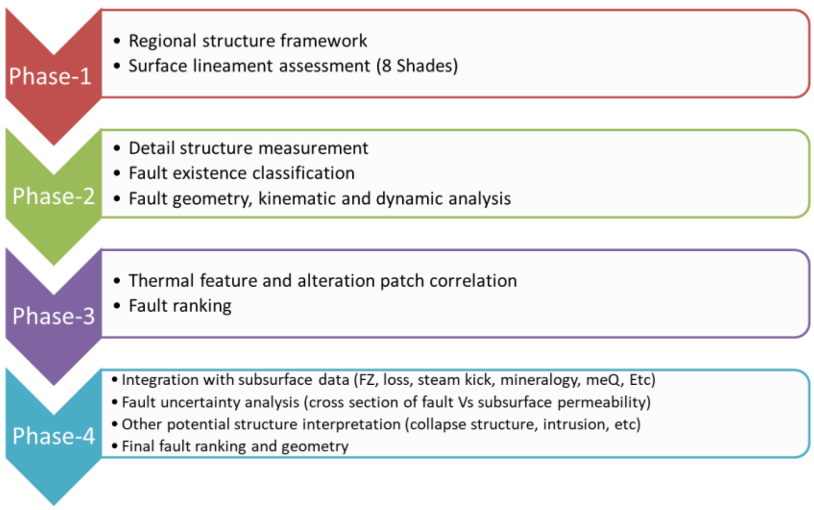


Figure 2: fault and structure permeability assessment workflow

The assessment started with desktop study and remote sensing interpretation to see the possible surface expression of the faults and structures from the surface image. Then, the ground checking was conducted to measure the evidence and confirm the coexistence of the faults. Later, these faults geometry were analyzed and being ranked based on the data existence and the connection with thermal features on the ground. The first rank fault may represent the high level of confidence the surface fault that might have good permeability from the surface expression only.

Meanwhile, the subsurface permeability indication coexisting from feed zones in the wells with its PI (Productivity Index) magnitude. In addition, the drilling data such as loss circulation, drilling breaks and steam kick are considered to indicate the permeability in the well that have no PI interpretation. The tracer chemical captured in the well after being injected in the other well shows the fluid flow pattern and connection among the wells also added the information of permeability. Eventually, the subsurface permeability assessment was supported by the geophysical data to see the extension of permeability beyond the wells.

The interpreted surface faults supported by subsurface permeability data yields the final fault ranking. These faults then being targeted in the drilling campaign with prioritize of high rank of the fault. In addition, to captures the uncertainty of the fault dip extension, the fault orientation assessment and damage zone analysis was conducted as a window for well targeting point and depth. The detail of tools and dataset that being used for the study is listed on figure 3.

Definition	Details	Type	Tools	Dataset
Best Fit Fault Target (integration surface and subsurface)	Surface Data	Hard	Lineaments and surface structure	LiDAR, Study UGM 2020, ITB 2014
			Field Measurement	Slickenside, brecciation, shear fracture (UGM '20)
			Thermal appearance	Fumaroles, springs, etc.
			Alteration patch	Study UGM 2020
		Soft	Kinematic analysis	Study UGM 2020
	Subsurface	Hard	Feedzones	PTS analysis (initial and current)
			Loss circulation, steam kicks	Mudlogs, drilling reports
			Tracer Test	Termochem '17 and '19
		Soft	MeQ Events population	Thesis and ITB study '20
			Focal mechanism analysis (MeQ)	Thesis and ITB study '20

Figure 3: Data availability

3. REGIONAL TECTONIC AND SURFACE FAULT ANALYSIS

The regional tectonic setting of Patuha which located in West Java is heavily influenced by subduction activity at the further south of Java Island. The subduction of oceanic crust of Indo-Australia plate and continental crust of Eurasia plate rapidly occurred at N20°E and about 6-7 cm/year (Pulunggono et al, 1994). Generally, the structure patterns developed in West Java are grouped into N-S of Sunda trends, NE-SW of Meratus trend and E-W of Java trend (Pulonggono and Martodjoyo, 1994) shown on Figure 3. In accordance to Satyana 2007, the regional tectonic in West Java also showing a similar conclusion that dominated with NE-SW, NW-SE, and E-W trends following the series of subduction phase. Whilst, the current maximum horizontal stress map shows NE-SW trend, parallel with the absolute plate motion directions (Modified from Hall and Morley, 2004 in Stingay et al, 2010).

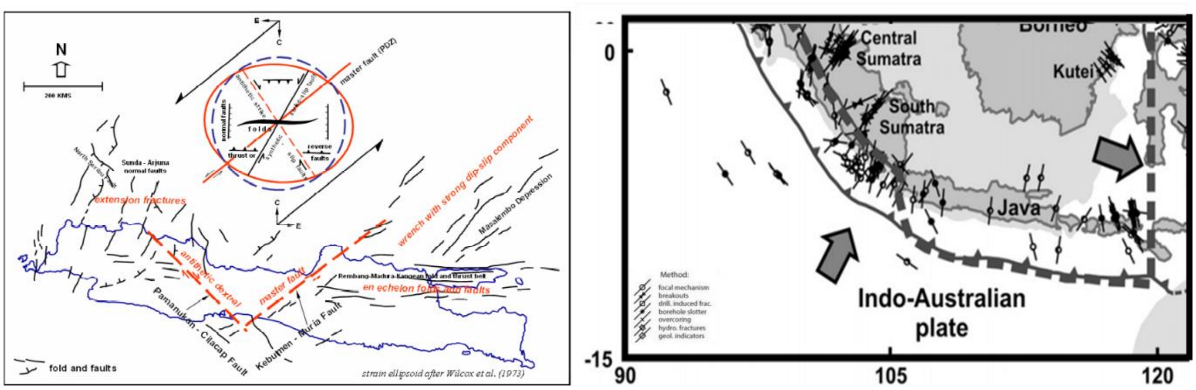


Figure 4. (Left) Regional tectonic framework and (Right) Current horizontal map from regional study (Stingay, 2010).

3.1 Remote Sensing Analysis

Remote sensing analysis of Patuha were done by using IFSAR (Interferometric Synthetic Aperture Radar) and updated with LiDAR (Light Detection and Ranging) image. The LiDAR surface has more advantage in spatial resolution than IFSAR, it has about 30 cm of horizontal and vertical resolution. The advance analysis also conducted on LiDAR surface, including analysis of aspect, depth of valley, drainages, hill shade, slope of hill, roughness pattern and ridge alignment. Those analysis yield interpreted surface lineament which extracted automatically by the software. However, for the structure interpretation, not only automatic extraction will be used but also the manual extraction being made to check for the consistency and confidence level of the existence of those lineaments.

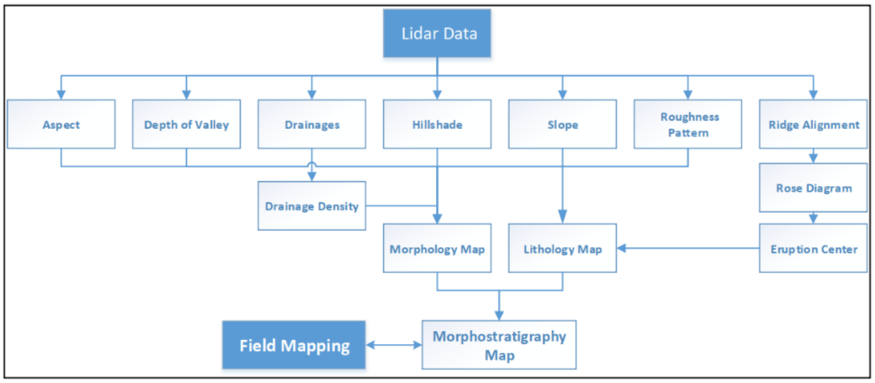


Figure 5: LiDAR analysis workflow

The lineament analysis done by comparing Lidar surface with eight different shade angles, there are 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. This is to eliminate the pseudo-lineament that might observed due to certain perspective. If the lineament still observed in more than four different shade angles, then the lineament existence will be considered as true. However, these lineaments preferably not to be concluded directly as faults thus structures. The interpreted lineament required to be checked on the field whether it is correlated to the structure or not.

3.2 Ground Truth Mapping

The detailed ground mapping conducted in 2019 with focus on the area of interest where the current prospect takes place. Based on the geology observation, found out there are 48 outcrops with structure evidence from 145 stop sites observed. Those evidence are slickenside, shear fracture, brecciation or fault alignment, minor fault plane, and joints. The other evidence is the surface thermal manifestation in terms of its type and elongation (figure 5).

Based on the surface data from the measurement. The geometry and kinematic analysis then were calculated to observe the potential fault existences, with their dip and regime. The result shows, the NE-SW trend has trans tensive (normal fault) with dip angle around (60-80). While for NW-SE and some NE-SW trend have pure Strike slip with dip angle around (80 -90 Deg). However, the interpretation is still inconclusive due to limited data to confirm the measurement. Later with the surface measurement combined with the Remote sensing interpretation, the Faults then were classified based on the confidence level to capture the existence and possible permeability.

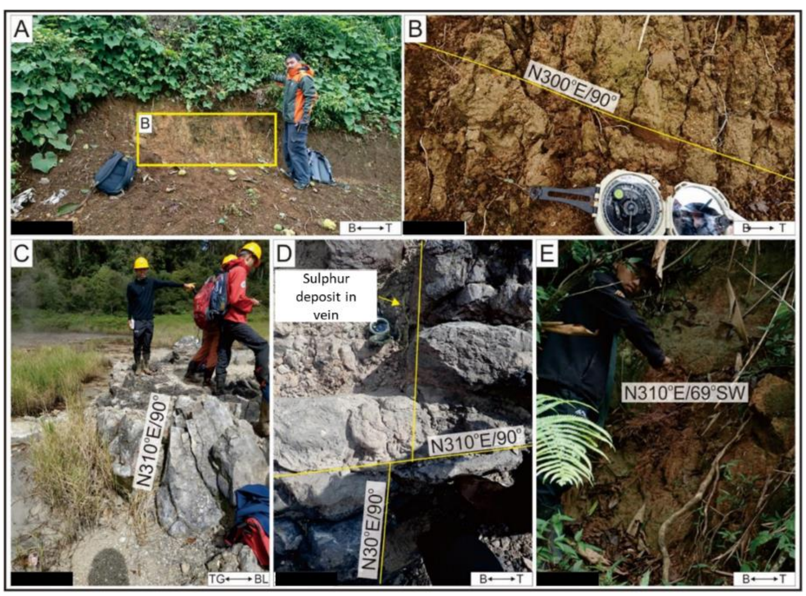
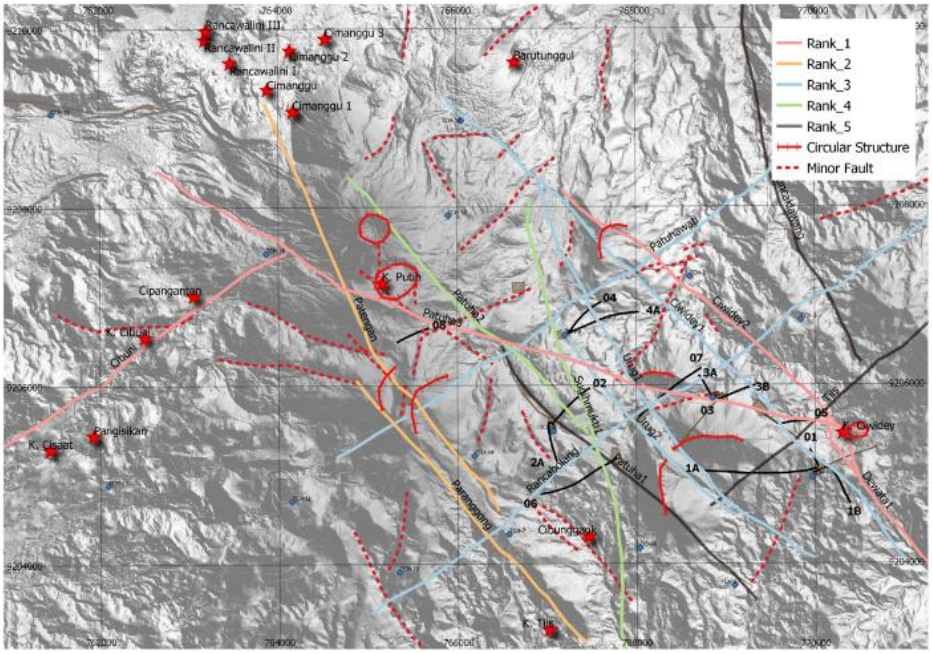


Figure 6: The fault measurement; (A) and (B) are the Babakan fault at the outcrop of pyroclastic lithology, (C) and (D) are the NW-SE and NE-SW faults at the outcrop of Andesite lava, (E) is the discontinuity surface at the slope of Mt, Urug, interpreted as the fault plane which triggers soil moved.

3.3 Surface Fault Ranking

Although the surface fault doesn't represent the subsurface condition directly, the surface fault ranking methods can give the general idea of structural trend accompanied by the surface expression as the evidence. Some parameters are considered to formulate the surface fault ranking. The high rank means the fault expected to be exist and permeable on surface and underneath. Firstly, the classification started with the existence of the lineament drawn on the LiDAR surface using the advance analysis. Secondly, the ground check conducted to prove the existence of the interpreted lineaments. Then, the faults that may associated with the surface thermal manifestation considered as the higher rank, more over the thermal activity that has signature of deep reservoir fluids such as fumaroles or Cl Springs.



No	Fault Name	Fumaroles / CL Springs	SO-4/ HCO-3 Springs	Alteration Patch	Surface measurement	Lineaments	Surface Fault Ranking
1	Cibuni	V	V	V		V	1
2	Patuha3	V		V	V	V	1
3	Ciwidey2	V			V	V	1
4	Dewata1	V			V	V	1
5	Paranggong		V	V	V	V	2
6	Patengan		V		V	V	2
7	Ciwidey1			V	V	V	3
8	Urug1			V	V	V	3
9	Rancabolang			V	V	V	3
10	Patuhawati			V	V	V	3
11	Urug2			V	V	V	3
12	Patuha2				V	V	4
13	Sugihmukti				V	V	4
14	Patuha1					V	5
15	Tiis				V	V	5
16	Puncaklawang					V	5

Figure 7: The surface fault ranking with Lidar as background (above) and it's supporting data (below)

Apparently, the higher rank fault mostly represented by the NW-SE trend followed by the NE-SW fault trend as the lower rank. The trend of NW-SE faults is generally associated with active fumarole of Kawah Putih and Kawah Ciwidey, while there is a distinctive trend of NE-SW Cibuni fault considered as high rank also due to associated with Kawah Cibuni fumarole. The lower rank of NE-SW fault trend barely associated with active thermal manifestation. Anyway, the subsurface evidence from well data and geophysical signature that strengthen the confidence level of final fault ranking later.

4. SUBSURFACE PERMEABILITY

4.1 Feed zone distribution

The main data to interpret the subsurface permeability is feed zone data from existing wells. To this moment, Patuha have 7 out of 14 PTS survey includes well of PPL-1, PPL-2, PPL-2A, PPL-3, PPL-3B, PPL-5 and PPL-7 although some of the wells might not be able to be logged down to TD of the well due to the obstruction within the wellbore. The rest of existing wells provided no PT/PTS data due to well condition allows.

The data from well drilling helps in interpreting the permeable zone particularly in area where the spinner data unavailable. The drilling data used in this interpretation are Steam kicks, Drilling Breaks, and Loss Circulation. These data taken as consideration to indicate the permeable zone perhaps the feed zones, moreover the temperature profile within this depth showing there is significant spikes of temperature during heating up survey.

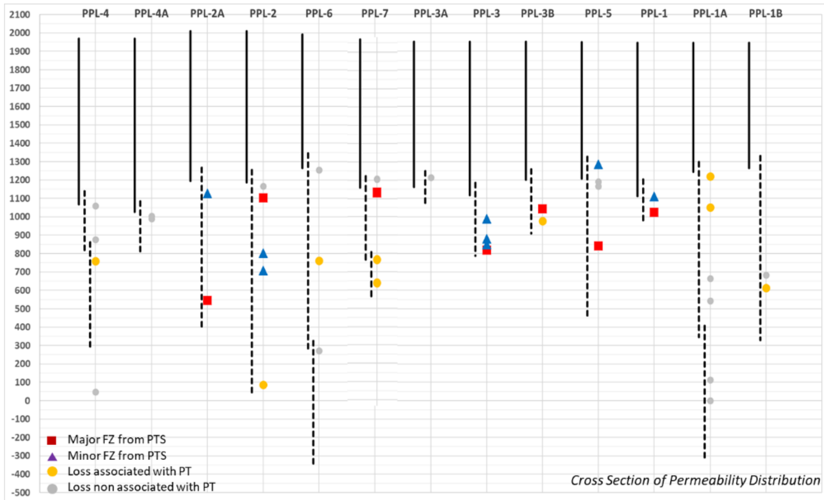


Figure 8: The cross section of vertical feedzone distribution.

Based on vertical feed zone distribution from offset well data, it is noticed that the major feedzone distributed within the elevation of 800-1250 masl, while the minor feedzone at the elevation of 500-700 masl. There is also an indication of coexistence of the potential feedzone at the deeper section around 0-150 masl by the indication of loss circulation associated with the temperature spikes during serial surveys as potential future target. Meanwhile from the horizontal distribution, there are some positive correlations with the interpreted surface faults (Ciwidey-1, Patuha-2, Patuha-3, and Rancabolang, Sugihmukti, and Patuha-1) even though there might be uncertainty in fault dip and the length of damage zone (figure 10).

4.2 Reservoir Tracer Test

The Reservoir Tracer Test (RTT) has been conducted in 2017 and 2019. The first test conducted on 2017 by injecting the PFC chemical in the well PPL-1B and it was first detected in well PPL-1 that located in the same pad about a month after (figure 9 on the left). The chemical recovery observed about 2,11% and it wasn't recovered on the other wells. Subsequently, the second test was conducted on 2019 by injecting the PDMCH (Perfluoro Dimethyl Cyclohexane) chemical in the well PPL-1A and it was observed the recovery only in well PPL-2A about 0.12% within almost 2 months.

The RTT supports the interpretation of well connectivity in the reservoir among PPL-1B and PPL-1 and in between PPL-1A and PPL-2A although the recovery factor was smaller (figure 9). It re-confirms the interpretation of major fault trend of NW-SE direction with domination of higher rank of fault. Despite the detail pattern of subsurface permeability remains unclear, at least the main trend of RTT result correlate with early hypothetic of fault permeability.

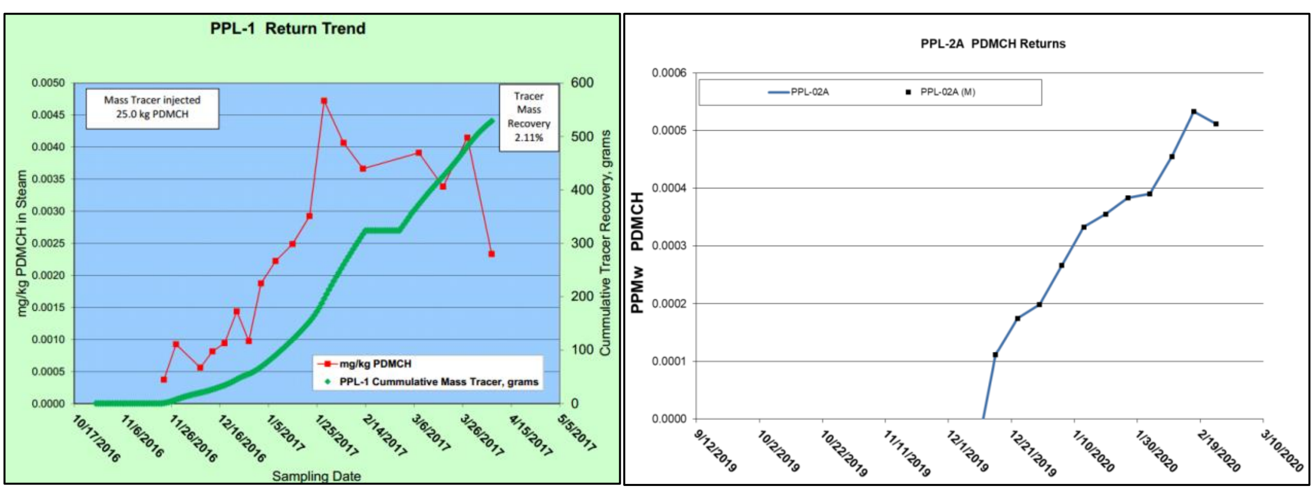


Figure 9: The tracer chemical returns on PPL-1 well (left) and PPL-2A well (right).

4.3 Micro-Earthquake

The Micro earthquake (MeQ) survey was conducted in 2019 for over 1 year period. The MeQ events captured more than 1000 events in eight seismometer stations (figure 9). The data acquisition was performed under production-injection condition. It is depicted in the figure below that the distribution of the events centralized in offset wells.

The advance analysis done within the MeQ events are the focal mechanism and shear wave splitting. For the 1st analysis, 10 high confidence and clear MeQ events were taken to be further analyzed for focal mechanism. The result shows the events appeared to have the main cluster and shows the right lateral strike-slip movement that align with the trend of Ciwidey-1 (blue beach ball), Patuha-3 (black beach ball) and some NNE-SSW (red beach ball) unidentified fault trends (Figure 10). Whilst the dip trends from the recorded event on beach ball showing some variation from 60 to 80 degrees. The second from shear wave splitting analysis indicated on figure 10 by the rose diagram. The result shows the possibility of discontinuity trend either from fractures or formation break. The result shows most of the rose diagrams are showing the trend parallel with fault trend of NW-SE with some NE-SW trend.

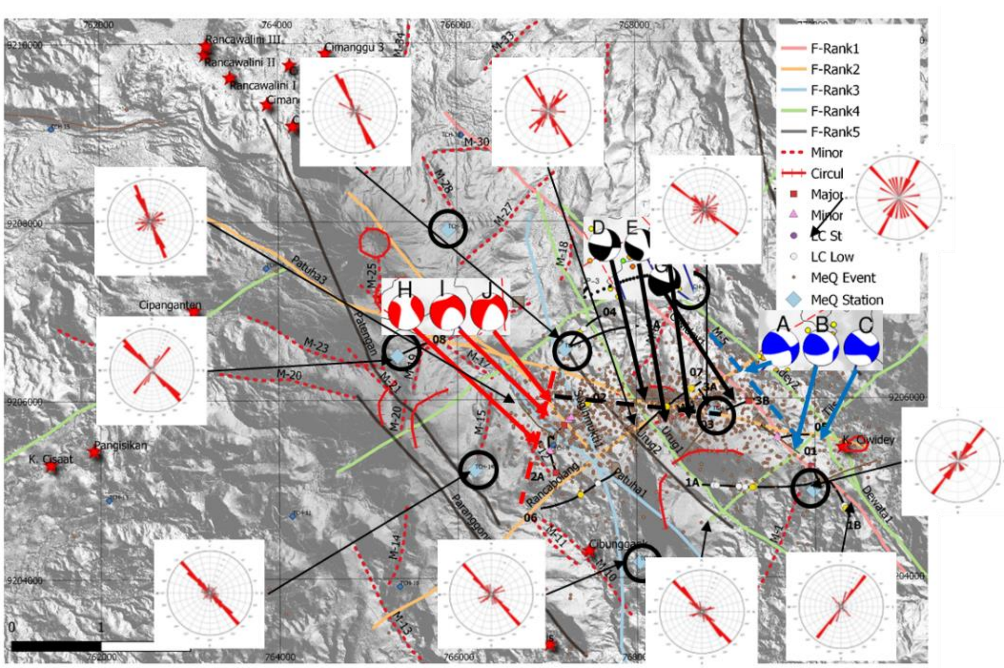
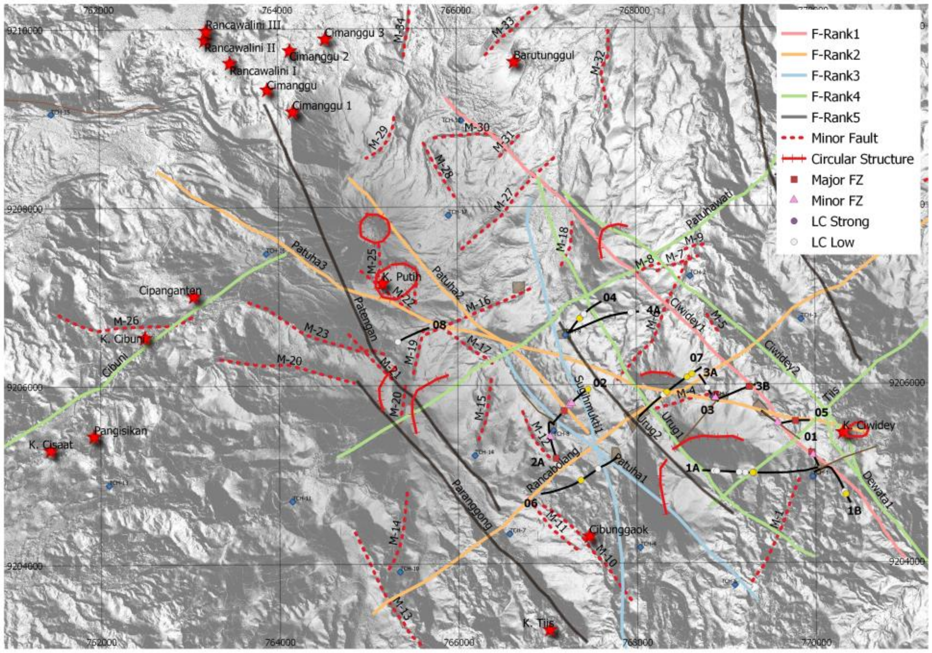


Figure 10: The focal mechanism and shear wave splitting

4.5 Final Fault Ranking

Apparently, the interpreted of surface faults may not necessarily correlate directly with the subsurface fault. Therefore, the integration of surface and subsurface fault trend should be established by the set of strong data and comprehensive analysis. The alignment of surface fault analysis that correlated with subsurface evidence that have the similar location and trend may show the existence of fault geometry and indicate the permeability extension in subsurface zone. Therefore, those correlations are being classified and yield the final fault ranking (most confidence). The higher rank represents the faults have been penetrated by wells and associated with major feedzones. In the opposite, the lower rank faults are associated with less penetrated well with minor feedzones occurrence or suspected feedzone evidenced by indirect fault and permeability data such as drilling loss circulation and supported with geophysical signatures (focal mechanism and shear wave splitting). The lower rank fault may indicate the low confidence level due to the fault might contribute to the permeability in the lower probability. This is caused by the faults may interpreted has closed permeability regime or lack of subsurface or well data which can support the interpretation and increase the confidence level. Therefore, with the new wells or more data available, the fault rank may be change in the future.

Based on the current interpretation (Figure 11), it shows that Ciwidey-1, Patuha-2, Patuha-3, and Rancabolang, are being a favorable well target for the moment. These high rank faults may give high possibility of success (POS) due to it has 1st and 2nd final fault rank based on the confidence level. While the other faults don't mean not favorable for the target, but the additional data from new wells and surveys may be needed to increase the level of confidence for well targeting.



Fault Name	Hard Data					Supporting Data			Surface Fault Ranking	Final Fault Ranking
	PTS Major	PTS Minor	Steam Kick	PT + Loss	RTT	MeQ Focal Mechanism	MeQ Shear Wave Splitting	Hypothetic fault kinematic		
Ciwidey-1	V		V	V	V	V	V	Strike-slip	3	1
Patuha-3	V		V			V	V	Strike-slip	1	2
Rancabolang	V			V			V	Normal	3	2
Patuha-2	V						V	Strike-slip	4	2
Sugihmukti		V					V	Normal	4	3
Patuha-1		V					V	Strike-slip	5	3
Urug-1				V			V	Strike-slip	3	4
Patuhawati				V				Normal	3	4
Tiis				V			V	Normal	4	4
Cibuni								Normal	1	4
Ciwidey-2							V	Strike-slip	1	4
Dewata-1							V	Strike-slip	1	4
Paranggong								Strike-slip	2	5
Patengan								Strike-slip	2	5
Urug-2							V	Strike-slip	3	5
Puncaklawang								Strike-slip	5	5

Figure 11: The Final Fault Ranking (above) and Data availability(below)

CONCLUSION

Most of identified final fault ranks are associated with subsurface evidence of permeability from wells and geophysical signature. It sharpens the interpretation of surface and subsurface connection. The most confident faults that may contribute to the permeability and increase the drilling success ratio are Ciwidey-1, Patuha-3, Rancabolang and Patuha-2 fault as 1st and 2nd Fault Rank. The rest of the faults might be or might not be significantly contribute to the permeability as the data set is not sufficient at the moment.

Meanwhile, the vertical Feedzone distribution from existing wells shows the major feedzone observed lies at 800-1250 masl, the minor feedzone at 500-700 masl while the suspected feedzone at 0-150 masl. This feedzones elevation are also suggested to be treated as one of the elements of well targeting. This also capturing the fault dip uncertainty that lies around 60 – 90 Degree based on surface measurement supported with focal mechanism and shear wave splitting data. Eventually, this is the initial study of the correlation of fault and structure with subsurface permeability. There are much more techniques can be applied to interpret the subsurface permeability pattern. The fault intersection, fault tail analysis, volcanic structure analysis, accommodation, and damage zone analysis and many more techniques can complete this approach in the future study.

Meanwhile the structure and permeability model will be updated once the new data from new wells such as Feedzone locations, fractures analysis from borehole image or other geophysical study will be integrated after Unit-2 well drilling campaign completed.

ACKNOWLEDGEMENT

The authors would like to recognize PT. Geo Dipa Energi especially Subsurface Department of Project Management Unit and Resource and Facility group for the support to complete this study and Management of PT. Geo Dipa Energi for granting permission to publish this study.

REFERENCES <HEADING 1 STYLE>

Chandra, V.R, Iskandar, C., Resource Target Area of Patuha, SPDEP Phase-1 work, (2020), Internal Report of Geodipa

Chandra, V.R, Ramadhan, Y., Detail Well Targeting of Patuha, SPDEP Phase-2 work, (2020), Internal Report of Geodipa

Elfina., Updated Conceptual Model of The Patuha Geothermal Field, Indonesia. United Nations University Geothermal Training Program (NU-GTP), (2017), Iceland

Hall, R.: Late Jurassic-Cenozoic Reconstruction of The Indonesian Region and The Indian Ocean, Tectonophysics, (2012), 570-571, 41pp.

ITB., Survey Micro Earthquake di Lapangan Geothermal Patuha, (2020), Internal Report of Geodipa

Layman, E, B., Soemarinda, S.: The Patuha Vapor-Dominated Resource West Java, Indonesia., Proceesing of the 28th Workshop on Geothermal Reservoir Engineering, Stanford, Ca, (2003), 10 pp.

Pulunggono, A., Martodjojo, S.: Perubahan tektonik Paleogen – Neogen merupakan peristiwa terpenting di Jawa. Proccedings Geologi dan Geotektonik Pulau Jawa, (1994), 37-50.

Satyana, A. H.: A “Terra Incognita” in petroleum exploration: New Considerations on the Tectonic Evolution and Petroleum Implications, Proceeding of the Indonesian Petroleum Association 31th Annual Convention and Exhibition, Indonesia, (2007), 22 pp.

Tingay, M., Morley, C., King, R., Coblentz, D., & Hall, R.: Present-day stress field of Southeast Asia, Tectonophysics, (2010), 482(1-4), 92-104